Cognitive Control of Behavior: ERP Correlates of Prepotent Response Inhibition in the Stroop Task

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Abstract

Recent research on cognitive control processes that support goal-directed behavior has distinguished between separable components of evaluative and regulative control. Evaluative control includes action-monitoring processes responsible for detecting the need for control and recruiting additional regulative resources when adjustments in control are necessary. Research has suggested that evaluative control is instantiated in the anterior cingulate cortex (ACC).

This project examines ERP correlates of cognitive control component processes in a modified Stroop color-naming task. Stimuli were words presented in colored script. Trials Types were congruent, neutral or incongruent. The relative frequency of the 3 Trial Types was varied across two Frequency Conditions: mostly congruent (MC; 80% congruent trials) and mostly incongruent (MI; 80% incongruent). Theory suggests that evaluative control is critical on incongruent trials in the MC condition. Consistent with this, previous neuroimaging research indicates that ACC is selectively activated in this condition.

In the current project, both phasic and slow wave ERPs were identified that vary with demands placed on cognitive control component processes across Trial Type and Frequency Condition. Moreover, these ERPs are significantly correlated with behavioral indices of task performance. This research establishes the utility of indexing ERPs in this modified Stroop task to examine neurocognitive processes underlying regulation of behavior. Application of this methodology to examine behavior regulation deficits associated with drug intoxication states and psychopathology is discussed.

Cognitive Control

Cognitive control refers to effortful activation and allocation of cognitive resources in the selection and processing of task-relevant information. Its function is critical for guiding and coordinating behavior in situations invloving response conflict and requiring inhibition of inappropriate prepotent response tendencies. Recent cognitive neuroscience research suggests two distinct components:

- Evaluative control: responsible for monitoring the need for control and signalling when adjustments are necessary; potentially instantiated in anterior cingulate cortex (ACC)

- Regulative control: responsible for activation and implementation of control-related processes; potentially instantiated in prefrontal cortex (PFC)

Carter et al. (*PNAS*, 2000) used a modified version of the Stroop task to selectively tax evaluative control and observed increased ACC activity with fMRI; the current project incorporates the same paradigm to identify ERP correlates of ACC activation & engagement of evaluative control.

Methodology

Participants
- 32 University students (16 female/16 male)

Description of Paradigm
- Participants performed an individual trial Stroop color-naming task
- Stimuli were words presented in colored script (red, blue, or green)

Independent Variables
Participants asked to name the script color of three different ***Trial Types***:
- Congruent trials (Ct): word and script color match (e.g., RED, GREEN)
- Neutral trials (Nt): word contains no color information (e.g., TOE, HAND)
- Incongruent trials (It): word and the script color differ (e.g., RED, BLUE)

Frequency of each Trial Type depended on the ***Frequency Condition***:
- Mostly congruent (MC) condition: 80% Ct, 10% Nt, 10% It
- Mostly incongruent (MI) condition: 10% Ct, 10% Nt, 80% It

**Evaluative control critical on incongruent Trial Types in mostly congruent Frequency Condition due to a high level of response conflict*

Method Details
- Stimuli presented for 500ms with a 1500ms response window
- Participants completed 4 blocks of 120 trials each
- Random ordering of Ct, Nt, and It, with probability according to Frequency Condition
- Verbal Response Time recorded online with digital trigger
- Combinations of 3 color words (RED, BLUE, GREEN) and 3 script colors for Ct and It
- Combinations of 3 script colors and 3 non-color words (TOE, HAND, WRIST) for Nt

Dependent Measures

Behavioral Indices
Stroop task performance was indexed with two separate behavioral measures: Response Time for correct trials, and overall Error Rate

Event-Related Potential (ERP) Indices
ERPs were sampled at 1000Hz in a 2000ms window initiating 500ms prior to stimulus onset. ERPs were filtered (0–15Hz), and eyeblink, artifact (signals > ±75uV rejected) and baseline corrected. Average ERP waveforms were computed for correct trials of each Trial Type for each Frequency Condition.

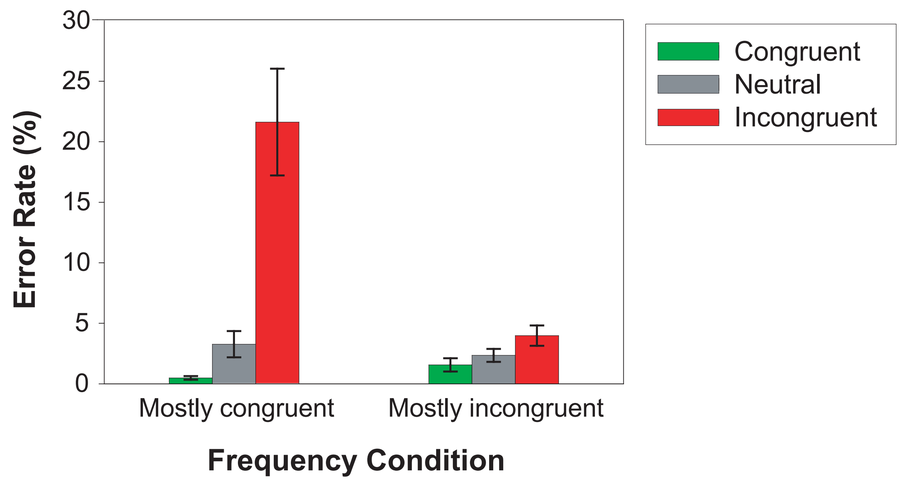
- ***N450*** is a negative anterior/frontal component of the ERP waveform suggested by previous research to index evaluative cognitive control in Stroop. Specifically, its topography and suggested source (ACC), latency, phasic nature, and sensitivity to condition effects support this assertion. N450 was quantified as the average response between 375ms and 475ms post-stimulus onset at the Cz scalp site.

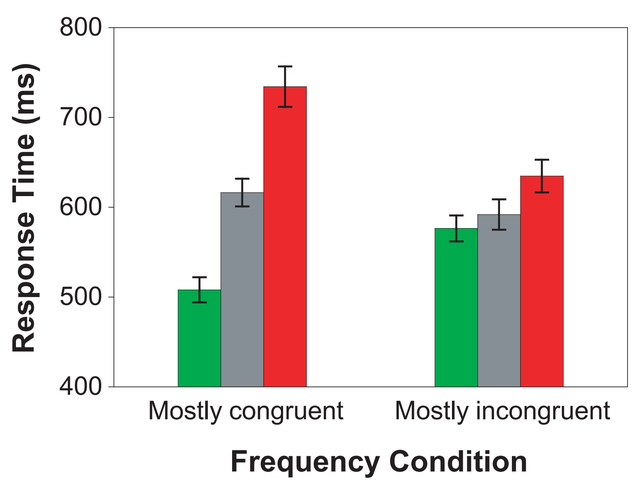
- ***Negative Slow Wave (NSW)*** is a negative anterior/frontal slow wave suggested by previous research to index regulative cognitive control. Specifically, its topography and suggested source (PFC), latency, relatively tonic nature and sensitivity to condition effects support this assertion. NSW was quantified as the average signal at the Fz scalp site in the last 400ms of the sampling window after the phasic components of the ERP had resolved.

Behavioral Measures

Error Rate:
A significant *Trial Type x Frequency Condition* interaction effect ($p<.001$) was observed for Error Rate, indicating that the simple effect of *Trial Type* was larger in the MC condition ($p<.001$, $Eta^2 = .619$) than in the MI condition ($p=.012$, $Eta^2 = .257$).

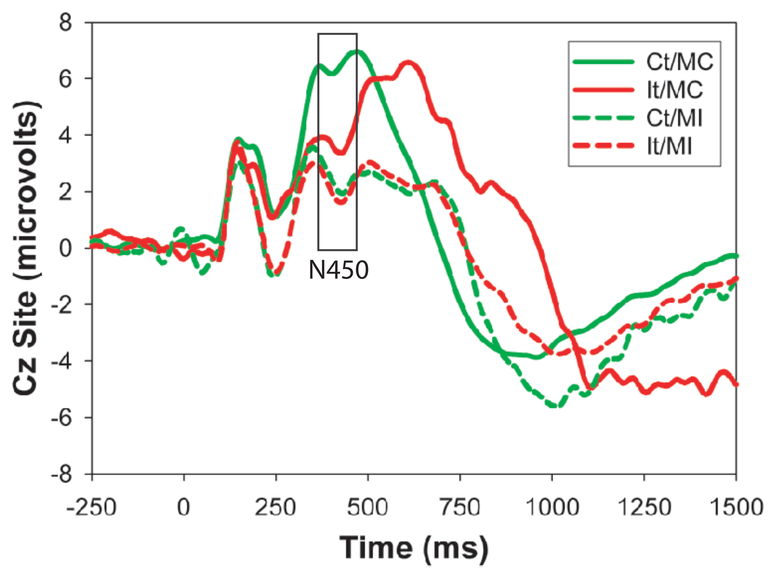
Reaction Time:
A significant *Trial Type x Frequency Condition* interaction effect ($p<.001$) was observed for Response Time, indicating that the simple effect of *Trial Type* was larger in the MC condition ($p<.001$, $Eta^2 = .883$) than in the MI condition ($p<.001$, $Eta^2 = .668$), consistent with our results for Error Rate and with the results of Carter et al. (2000).

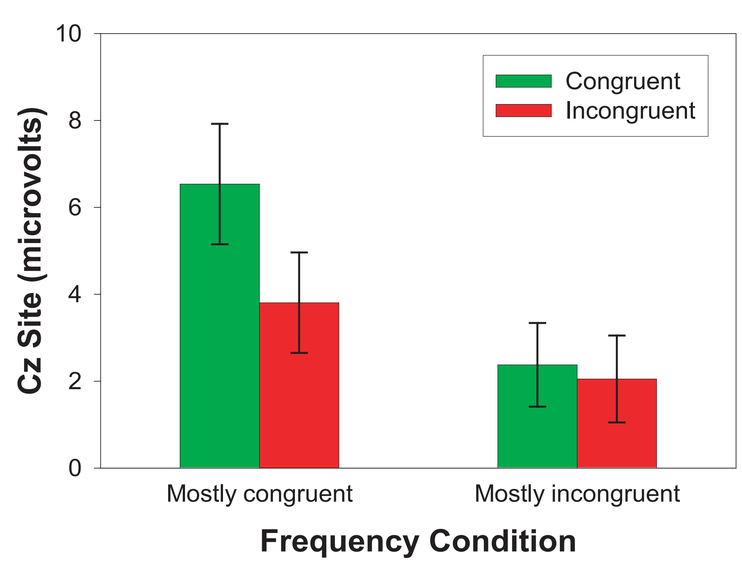




N450

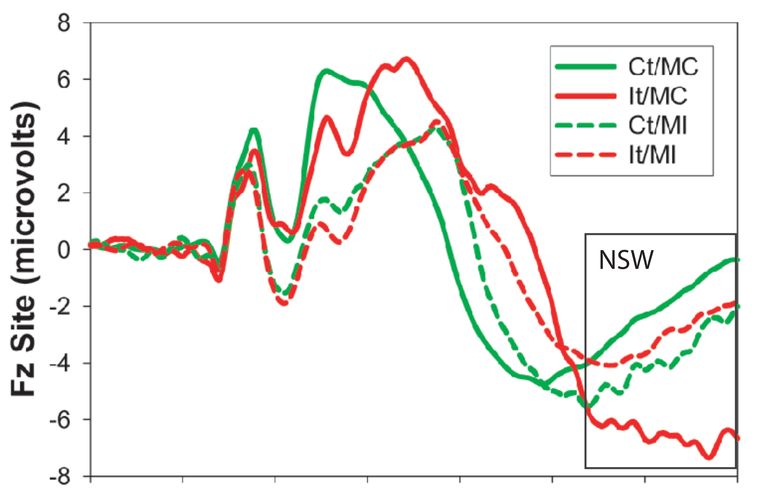
The design of Carter et al. (2000) included only congruent and incongruent trials, so the neutral Trial Type was not included in ERP analyses. P-values for the *Trial Type x Frequency Condition* interaction effect for sites along the midline were as follows: p(Fz)=.339, p(FCz)=.127, p(Cz)=.023, p(Pz)=.031. Additional analyses were conducted using data from the Cz scalp site, showing that the simple effect of *Trial Type* was significant in the MC condition ($p=.006$, $Eta^2 = .408$) but not the MI condition ($p=.548$, $Eta^2 = .025$).

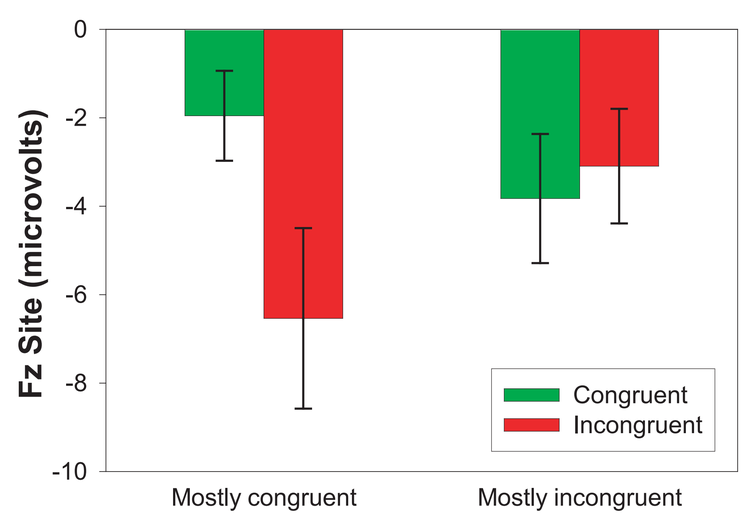




Negative Slow Wave (NSW)

P-values for the *Trial Type x Frequency Condition* interaction effect for sites along the midline were as follows: p(Fz)=.004, p(FCz)=.004, p(Cz)=.012, p(Pz)=.004. Additional analyses were conducted using data from Fz scalp site, showing that the simple effect of *Trial Type* was significant in the MC condition ($p=.010$, $Eta^2 = .369$) but not the MI condition ($p=.300$, $Eta^2 = .071$).





Correlations Between Behavioral & ERP Indices

Interference contrasts were calculated for Response Time, N450, and NSW as the average difference between incongruent and congruent Trial Types. Correlation coefficients between these interference contrasts are show below, both overall and within each Frequency Condition.

Frequency Condition	RT & N450	RT & NSW	N450 & NSW
Overall	r = -.400*	r = -.486*	r = .109
MC	r = -.344	r = -.170	r = -.192
MI	r = -.119	r = -.159	r = .555*

*p<.05

Conclusions

- The behavioral effects observed in this study are similar to those reported by Carter et al. (2000), suggesting our manipulations successfully altered the burden placed on evaluative cognitive control. Furthermore, we identified two components of the ERP waveform, N450 and NSW, that varied across Trial Type and Frequency Condition, and changes in these components were significantly correlated with behavioral indices of task performance. This suggests that N450 and NSW can be used to monitor ACC activity relating to changes in evaluative cognitive control necessary for adaptive performance in the Stroop task.

- ERP indices of evaluative cognitive control have the advantage of enhanced temporal resolution compared to fMRI. Thus it is possible to address questions regarding the relationship between N450 and NSW on individual trials. If N450 represents phasic activation of evaluative control calling for increased regulative control, the regulative response could be captured in the tonic NSW signal at the end of each trial. The correlations observed between N450 and NSW within each Frequency Condition hint at this type of relationship, but the results are not entirely clear and additional work is necessary to adequately assess this possibility.

- The selective assessment of evaluative control within this paradigm will be useful for examining behavior regulation deficits associated with drug intoxication and psychopathology. For example, recent work in our lab has demonstrated that acute alcohol intoxication leads to impairment of cognitive control function. ERP recordings of intoxicated and non-intoxicated individuals within the current paradigm will allow us to investigate alcohol's selective effect on evaluative cognitive control. The utility of this paradigm also extends to examinations of cognitive control dysfunction in schizophrenia and psychopathy.

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